Nat Hazards (2012) 61:893–910
DOI 10.1007/s11069-011-9942-1

ORIGINAL PAPER

Location-specific weather predictions for Sriharikota (13.72°N, 80.22°E) through numerical atmospheric models during satellite launch campaigns

D. Bala Subrahamanyam · Radhika Ramachandran · S. Indira Rani · S. Sijikumar · T. J. Anurose · Asish Kumar Ghosh

Received: 20 October 2009 / Accepted: 10 August 2011 / Published online: 28 August 2011
© Springer Science+Business Media B.V. 2011

Abstract Accurate knowledge of different meteorological parameters over a launch site is very crucial for efficient management of satellite launch operations. Local weather over the Indian satellite launch site located at Sriharikota High Altitude Range (SHAR: 13.72°N, 80.22°E) is very much dependent on the atmospheric circulation prevailing over the Bay of Bengal oceanic region and topography-induced convective activities. With a view to providing severe weather threat prediction in terms of launch commit criteria (LCC), two numerical atmospheric models namely high-resolution regional model (HRM) and advanced regional prediction system (ARPS) are made operational over SHAR in a synoptic and mesoscale domain, respectively. In the present research article, two launch campaigns through Polar Satellite Launch Vehicle (PSLV-C11 and PSLV-C12) when contrasting weather conditions prevailed over the launch site are chosen for demonstration of potential of two models in providing location-specific short-to-medium-range weather predictions meeting the needs of LCC. In the case of PSLV-C11 campaign, when the launch site underwent frequent thundershower-associated rainfall, ARPS model–derived meteorological fields were effectively used in prediction of probability of the wet spells. On the other hand, Bay of Bengal underwent severe cyclonic storm during PSLV-C12 campaign, and its formation was reasonable captured through HRM simulations. It is concluded that a combination of HRM and ARPS provide reliable short-to-medium-range

D. Bala Subrahamanyam (✉) · S. Sijikumar · T. J. Anurose
Space Physics Laboratory, Vikram Sarabhai Space Centre, Department of Space, Government of India, Indian Space Research Organization, Thiruvananthapuram, Kerala 695 022, India
e-mail: subrahamanyam@gmail.com

R. Ramachandran
ISRO Technical Liaison Unit, Embassy of India, Paris, France

S. Indira Rani
National Centre for Medium Range Weather Forecasting, Ministry of Earth Sciences, Government of India, Noida, Uttar Pradesh 201 307, India

A. K. Ghosh
Meterological Facility, Satish Dhawan Space Centre, SHAR, Sriharikota, Andhra Pradesh 524124, India

weather prediction over SHAR, which has got profound importance in launch-related activities.

Keywords Advanced regional prediction system (ARPS) · Chandrayaan · High-resolution regional model (HRM) · Numerical weather prediction (NWP) · Launch commit criteria (LCC) · Nowcasting · Thunderstorms

1 Introduction

Knowledge of meteorology forms the basis of scientific weather forecasting. The evolution of operational numerical weather prediction (NWP) from larger to smaller scales partially reflects the increased computer power that has allowed global models to resolve more details of atmospheric flow fields (Cox et al. 1998; Pielke 1984). In the Indian scenario where the most of agricultural industries depend on summer monsoon rainfall, several atmospheric models are run at different organizations to deliver regular forecasts to community and media with a special emphasis on prediction of onset of monsoon and expected amount of rainfall (Das et al. 2002; Singh et al. 2005). However, operational forecast models run by meteorological departments are not meant for prediction of local weather with the high spatial and temporal resolutions within a specific time window (Radhika 2008; Radhika et al. 2006). In this regard, accurate weather predictions during satellite launch campaign over the launch site become very crucial for efficient management of launch time operations (Manobianco et al. 1996; Radhika et al. 2006; Rakesh et al. 2007). During such campaigns, accurate information on the magnitude of surface winds, vertical wind-shears, amount of precipitation, cloud cover fraction and probability of thunderstorm kind of events at very fine spatial and temporal resolutions is required for efficient time management of satellite launch activities (Dudhia 1993; KSC Press Release 2000; Manobianco et al. 1996; Radhika et al. 2006; Snook et al. 1977). Therefore, additional procedures based on current observations (surface and upper air observations, Radar and satellite) are required to inform on imminent weather events and to warn if necessary.

As part of launch campaign activities, once the satellite payload is declared ready for its space journey, the mission team used to define a launch window extending over a few days with a specific time slot for the launch. Definition of such a time slot and launch window is one of the most crucial tasks, and it requires adequate knowledge on local weather over the launch site in terms of the launch commit criteria (LCC) so as to avoid any hazardous events due to bad weather (Case et al. 2002; Manobianco et al. 1996). Each launch vehicle has a specific tolerance for wind shear, cloud cover and temperature, whereas lightening constraints are common for all types of vehicles. Thus, NWP activities through various atmospheric models during launch campaign are ultimately intended to provide short-range (<48 h) forecasts of winds, temperature, moisture, clouds and any hazardous weather event such as thunderstorm over the launch site with good accuracy. The local weather over the Indian satellite launch station—Sriharikota High Altitude Range (SHAR)—located on south-eastern coastal site is highly dependent on atmospheric wind circulation prevailing over its adjoining Bay of Bengal (BoB) oceanic region and topography-induced convective activities. Keeping these meteorological features over SHAR in background and to meet the forecasting needs for LCC, two numerical atmospheric models, namely high-resolution regional model (HRM) and advanced regional prediction system (ARPS) model, are made operational. On one hand, the HRM simulations provide valuable information on meteorological conditions prevailing over the Indian subcontinent and its adjoining oceanic

counterpart with a special emphasis on formation of any hazardous weather event such as cyclonic storms and its movement. On the other hand, the ARPS model is being run regularly at different time intervals at very high horizontal and vertical resolution for alerting the mission team on probability of thunderstorm occurrence and rainfall time slots over the launch site, if any. With a view to showing the potential of these two atmospheric models in varying meteorological conditions, we make use of two consecutive launch campaigns, namely PSLV-C11 and PSLV-C12, which took place in the month of October 2008 and April 2009, respectively, when SHAR underwent two contrasting weather events.

1.1 Scope of the paper

This research article reports the importance of NWP activities with the aid of two atmospheric models—HRM and ARPS—in terms of LCC for satellite launch campaigns. Two launch campaigns in contrasting meteorological background are chosen for detailed investigation on the potential of these models. The paper is divided into five sections. The first chapter introduces the main objective of the research article. In Chapter 2, we provide important information on HRM and ARPS models used in the present study. Their detailed description and basic differences are tabulated in Tables 1, 2 and 3. Chapter 3 introduces the geographical map of SHAR—the launch site and topographic contours fed to the two models. Chapter 4 deals with the Results and Discussions and is organized into three subsections in which the quantitative details on how the two campaigns differed from each other and then the performance of two models are presented. Finally, we present our concluding remarks in Chap. 5.

2 An overview of HRM and ARPS model

In a broad sense, atmospheric models can be classified into two categories: (1) hydrostatic and (2) non-hydrostatic models. The first class of models assumes hydrostatic equilibrium of atmosphere, while the second class is useful in dealing non-hydrostatic processes and their effects become more useful when the length of the feature is approximately equivalent to its height (Anthes and Warner 1974; Bannoon 1995; Pielke 1984). Thus, non-hydrostatic models can be quite sensitive to small differences in atmospheric structure in vertical. Between the two models used in the present study, HRM assumes hydrostatic approximation, while ARPS is a non-hydrostatic model.

2.1 High-resolution regional model (HRM)

HRM is basically a hydrostatic regional model developed for shared memory computers at Deutscher Wetterdienst (DWD) of Germany that serve as one of the flexible tools for NWP for the usage in meso-α and meso-β scales and is widely used by several meteorological services, universities and research institutes spanning a large domain of the globe (Majewski 2009). The model consists of topographic data sets which can be obtained in regular or rotated latitude/longitude grid for any region of the world at mesh sizes between 30 km and 5 km. Several options exist within the HRM to derive the initial state and lateral boundary conditions; however, in the present study, we have derived the initial state and lateral boundary conditions of the HRM from interpolation of the analysis and forecasts of DWD's global model GME (grid spacing 40 km, 40 layers) to the HRM grid, respectively. Since the volume of the global data set (>10 Giga-Bytes) is much too big for a timely

Table 1 An overview of the HRM (adopted from Majewski 2009)

Prognostic variables	Diagnostic variables
Surface pressure	Vertical velocity
Temperature	Geopotential
Water vapour	Cloud cover
Cloud water	Diffusion coefficients
Cloud ice	
Ozone (optional)	
Horizontal wind (zonal and meridional components)	
Several surface/soil parameters	
Numerics of HRM	
Regular or rotated latitude/longitude grid	
Mesh sizes between 0.25° and 0.05° (~28–6 km)	
Arakawa C-grid, second-order centred differencing	
Hybrid vertical coordinate: 20–40 layers	
Split semi-implicit time stepping; $\Delta = 150$ s at $\Delta = 0.25°$	
Helmholtz equation solved by a direct method (FFT and Gauss solver)	
Lateral boundary formulation	
Radiative upper boundary condition as an option	
Linear fourth-order horizontal diffusion, slope correction for temperature	
Adiabatic implicit non-linear normal mode initialization or diabatic (incremental) digital filter initialization	
Physical Parameterizations of HRM	
δ-Two-stream *radiation* scheme including long- and shortwave fluxes in the atmosphere and at the surface; full cloud-radiation feedback; diagnostic derivation of partial cloud cover (rel. hum. and convection)	
Grid-scale *precipitation* including parameterized cloud microphysics	
Mass flux *convection* scheme differentiating between deep, shallow and mid-level convection	
Level-2 scheme of *vertical diffusion* in the atmosphere, similarity theory at the surface	
Subgrid-scale orographic (SSO) effects (blocking and wave breaking) due to unresolved orography	
Seven-layer *soil model* including snow and interception storage	
Sea ice model	

Table 2 ARPS model run configuration

Model domain centre	SHAR (13.7167°N, 80.2167°E)
Model configuration	3-D vertical column mode
Model integration time step	6 s
Terrain option	30-s terrain data (USGS)
Model grid set-up	Vertical grid stretching
Model initialization data	Pisharoty GPS high-resolution data
No. of vertical levels in the model	35 levels (vertical stretching)
Initialization of base-state fields	External sounding data
Potential temperature perturbation	Symmetric random initial perturbation

Table 3 Comparison between HRM and ARPS model

	High-resolution regional model (HRM)	Advanced regional prediction system (ARPS)
Dynamics	Hydrostatic	Non-hydrostatic
Usage	Different mesoscale processes	Storm model
Developed by	Deutscher Wetterdienst (DWD), Germany	Centre for Analysis and Prediction of Storms (CAPS) of Oklahoma State University, USA
Model domain	65°E to 95°E, 0 to 30°N	($\sim$50 km $\times$ 50 km) centred around SHAR
Horizontal resolution	0.10° ($\sim$10 km)	$\sim$1 km
Topography resolution	0.10° ($\sim$10 km) prepared by DWD	30 s ($\sim$1 km), USGS
Vertical levels	40 levels with vertical stretching; Model ceiling is kept at 10 hPa ($\sim$31 km)	35 levels with vertical stretching; model ceiling is kept at 100 hPa ($\sim$16 km)
Initialization and lateral boundary conditions	Global model output for the HRM domain (horizontal resolution at $\sim$40 km)	High-resolution GPS ascent data (maximum permissible levels = 600); symmetric initial perturbations for LBC
Prognostic variables	Surface pressure, temperature, water vapour, cloud water, cloud ice, horizontal wind (zonal and meridional)	Potential temperature, horizontal wind (zonal and meridional), Water substance, subgrid-scale turbulent kinetic energy
Time integration scheme	Split semi-implicit with $\Delta t = 150$ s	$\Delta t = 6$ s
Atmospheric boundary layer parameterization schemes	Level-2 scheme vertical diffusion in the atmosphere, Similarity theory at the surface	Compute the time evolution of boundary layer depth in response to the surface heat fluxes or user specified boundary layer depth
Turbulent fluxes	Louis (1979) in the prandtl layer and Mellor and Yamada (1974) for the boundary layer and free atmosphere	Modified Businger formulation (Businger et al. 1971)
Convective parameterization schemes	Tiedtke (1989)	Kuo (1965, 1974), Kain and Fritsch (1993)
Soil model	The multilayer soil model (Heise and Schrodin 2002) with seven layers	Noilhan and Planton (1989), Pleim and Xiu (1995)

transfer, DWD provides to each HRM user GME data sets tailored to the respective local HRM domain. Thus, the amount of GME data which has to be transferred via the internet can be reduced drastically. For a typical HRM domain of 4,000 $\times$ 4,000 km^2, the GME data set (initial state plus 26 lateral boundary data sets at 3-hourly intervals) needed for a 78-h HRM forecast is in the order of (1 + 26)*4.7 MByte = 127 MByte for the full version. An internet connection with a bandwidth between 256 and 512 KB/s is fast enough for a timely reception of the GME data. In the present case, the initial and lateral boundary conditions data from DWD's global model GME for 0000 GMT run are available for HRM runs for the Indian subcontinent by 0330 GMT itself, which is quite early as compared to other global model outputs. Most of the technical features of HRM resemble with the German global model GME (Majewski 2009). The prognostic equations of HRM

are expressed in differential forms in terms of spherical coordinates and a hybrid (sigma-pressure) vertical coordinate in Arakawa C-grid with second-ordered centred difference scheme, and the time integration is through a semi-implicit scheme. Radiative transfer of solar and thermal radiation in clear and cloudy atmospheres is based on a scheme developed by Ritter and Geleyn (1992). Cloudiness is derived from specific cloud liquid water and ice contents, relative humidity, convective activity and stability (Ritter and Geleyn 1992). The grid-scale precipitation scheme of HRM includes parameterized cloud microphysics with the three prognostic water species: water vapour, cloud liquid water and cloud ice. The precipitation phases (rain and snow) are treated diagnostically. The parameterization of deep and shallow convection in HRM is based on a mass flux approach (Tiedtke 1989). The convection scheme distinguishes three different convection types, namely shallow, mid-level and penetrative (deep). The three-dimensional convergence of water vapour is used as closure assumption for shallow and deep convection. Convective precipitation is initiated only if the cloud depth exceeds 3,000 m over land and 1,000 m over water. Table 1 provides basic description of the HRM in detail. In the present study, initial and lateral boundary conditions for the HRM are derived from forecasts of the global model GME of DWD.

2.2 Advanced regional prediction system (ARPS)

In the literature, we find mention of development of three-dimensional non-hydrostatic modelling for convection since the mid-1970s (Xue et al. 2000 and references cited therein). The development of non-hydrostatic models and rapid increase in computer powers have made the explicit prediction of thunderstorm into a reality. With a view to demonstrating the practicability of storm-scale numerical weather prediction, the advanced regional prediction systems (ARPS) model was developed by the Center for Advanced Prediction of Storms, Normal, Oklahoma, USA (Xue et al. 2000, 2001, 2003). The ARPS is designed from the beginning to serve as an effective tool for basic and applied research and as a system suitable for explicit prediction of convective storms as well as weather systems at other scales. The ARPS includes its own data ingest, quality control and objective analysis packages, a data assimilation system that includes single-Doppler velocity and thermodynamic retrieval algorithms, the forward prediction component, and a self-contained post-processing, diagnostic and verification package. The forward prediction component of the ARPS is a three-dimensional, non-hydrostatic compressible model formulated in generalized terrain-following coordinates. The model employs advanced numerical techniques, including monotonic advection schemes for scalar transport and variance-conserving fourth-order advection for other variables. The model also includes state-of-the-art physics parameterization schemes that are important for explicit prediction of convective storms as well as the prediction of flows at larger scales (Case et al. 2002; Xue et al. 2000).

ARPS is basically a primitive equation model based on compressible Navier–Stokes equations describing the atmospheric flow. The prognostic variables are Cartesian wind components, perturbation potential temperature and pressure, subgrid-scale turbulent kinetic energy (TKE), mixing ratios for water vapour, cloud water, rain water, cloud ice, snow and hail. The spatial discretization is achieved by second-order quadratically conservative and fourth-order quadratically conservative finite differences for advection and second-order differencing for other terms, while temporal discretization is treated with a second-order leap-frog scheme for large time steps with Asselin time filter option.

In the present study, ARPS is initialized with a high-resolution GPS sounding ascent data in conjunction with 30-second terrain elevation data (source: United States Geographical Survey). Table 2 describes ARPS model run configuration used in the present study, while Table 3 provides a glimpse of major differences between the two models. One of the basic differences in the two model simulations is that HRM is initialized with a global model analyses and its lateral boundary conditions are taken from the forecast of global model, whereas the base-state field for ARPS domain is generated through vertical column GPS ascents and potential temperature perturbations are generated through symmetric random option available within the model code (Subrahamanyam et al. 2006, 2008; Xue et al. 1995).

3 Sriharikota: the satellite launch station of ISRO

The launch site of the Indian Space Research Organization (ISRO) is located at the Sriharikota High Altitude Range (SHAR: 13.7167°N, 80.2167°E), which is a tiny island, close to the Eastern Coast having a complex terrain with the Eastern Ghats located on its west and surrounded by the Pulicat Lake and Bay of Bengal on the east (Fig. 1a, b). The launch site very well falls in the vicinity of tropical cyclone landfall zone (Singh et al. 2005). It is therefore obvious that the underlying complex terrain could very well affect the local winds, resulting at times in the developments of hazardous thunderstorms. The depressions that develop over the Bay of Bengal can also affect the short-term weather of SHAR. Figure 1a, b depicts the topography contours used in the two models—HRM and ARPS, respectively. The HRM topography data with a horizontal resolution of 0.10° (~10 km) shown in Fig. 1a are prepared at the DWD, Germany, while we make use of the United States Geographical Survey (USGS) surface elevation data available at 30 s (~1 km) for the mesoscale model ARPS which is customized for simulating highly localized features.

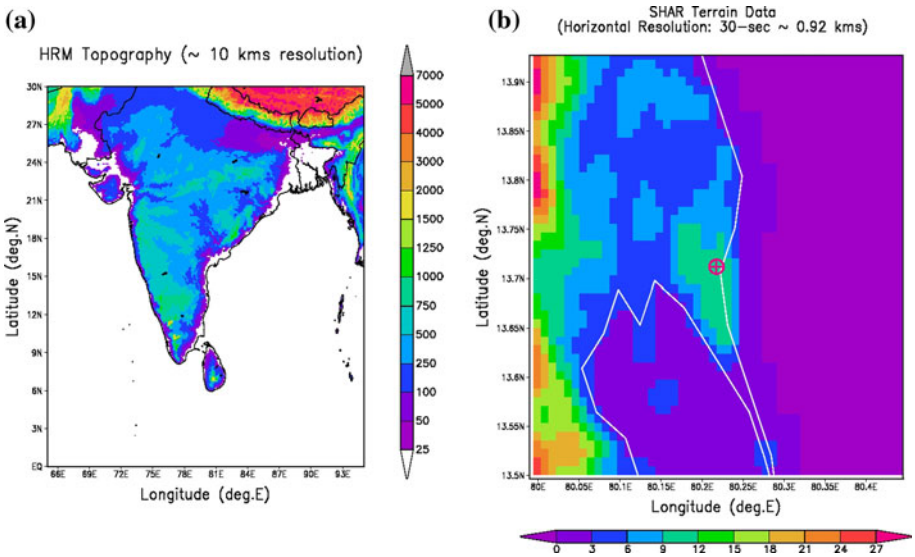

Fig. 1 **a** High-resolution regional model (HRM) topography at a horizontal resolution of 0.10° (~10 km); **b** USGS topography at a horizontal resolution of 30 s (~1 km) fed to ARPS model

4 Results and discussion

4.1 Ambient meteorological conditions prevailing during PSLV-C11 and PSLV-C12 launch campaigns

As per climatology of the Indian subcontinent, the ambient meteorological conditions are largely governed by monsoonal winds. The subcontinent experiences wet and rainy season during its summer monsoon (also referred to as south-west monsoon) in the month of June to September when the moist air from oceanic regions intrudes the continent resulting into large precipitation spells wide spread over the season. The month of March to May over the subcontinent is considered as pre-monsoon period when SHAR (the launch site) experiences quite hot and summer environmental conditions with very less rainfall resulting in a magnitude of about 5 to 7.5 cms (Indian Meteorological Department Website: http://www.imd.gov.in/). On the other hand, the period of October to December is considered as post-monsoon season, when SHAR experiences frequent rainfall amounting from 75 to 100 cms, almost an order larger than that observed during the pre-monsoon season. The present research article is confined to two launch campaigns, namely—PSLV-C11 and PSLV-C12 (hereafter referred to as C-11 and C-12 campaigns)—which took place on 22nd October 2008 and 20th April 2009, respectively. The meteorological conditions prevailing over the launch site during C-11 and C-12 campaigns in the present study are taken to be representative of post-monsoon and pre-monsoon seasons, respectively.

The month of October happens to be the period when retrieval of the Indian summer monsoon starts with setting up of north-east monsoon over SHAR. The period of C-11 campaign coincided with the onset of NE monsoon when the launch site underwent frequent thundershowers and associated rainfall; hence, it became quite crucial to know the exact timings of rainfall slots. With a view to representing ambient meteorological conditions prevailing over the launch site in terms of surface layer observations obtained from Automatic Weather Station installed at SHAR (Manikiam et al. 2008), we show monthly variations in surface pressure, air temperature, relative humidity and wind speed for the months of October 2008 and April 2009 in Figs. 2a–d and 3a–d, respectively. Daily mean values of these parameters with their standard deviation are shown as thick black lines, while the minimum and maximum values of the concerned parameter in red and green colour, respectively, envelop the mean values in the Figs. 2a–d and 3a–d. Surface layer barometric variations during both the campaigns were ranging from 1,001 to 1,014 hPa (Figs. 2a, 3a). Air temperature magnitudes during C-12 campaign were marginally higher than that observed on C-11 campaign (Figs. 2b, 3b). Similarly, relative humidity measurements during C-12 campaign were marginally lower than that seen in C-11 campaign (Figs. 2c, 3c), and these features in temperature and humidity are attributed to contrasting weather prevailing over the two campaigns. These surface layer observations provide a statistical support to our assumption that C-11 and C-12 can be taken as representative of post- and pre-monsoon season. Surface layer winds varied between 0 ms^{-1} and 6.60 ms^{-1} during C-11 campaign, while wind magnitudes went up to 7.90 ms^{-1} in C-12 campaign (Figs. 2d, 3d). The detailed statistics of all these parameters with their range, mean and standard deviation for the two campaigns are tabulated in Table 4 for quick reference.

One of the important differences in prevailing ambient meteorological conditions during C-11 and C-12 campaigns was the amount of rainfall observed over the launch site. During C-11 campaign, the launch site underwent onset of NE-monsoon and experienced frequent rainy slots with few breaks. Figure 4 shows daily and total accumulated rainfall observed from SHAR Automatic Weather Station. It can be seen from Fig. 4 that the launch site

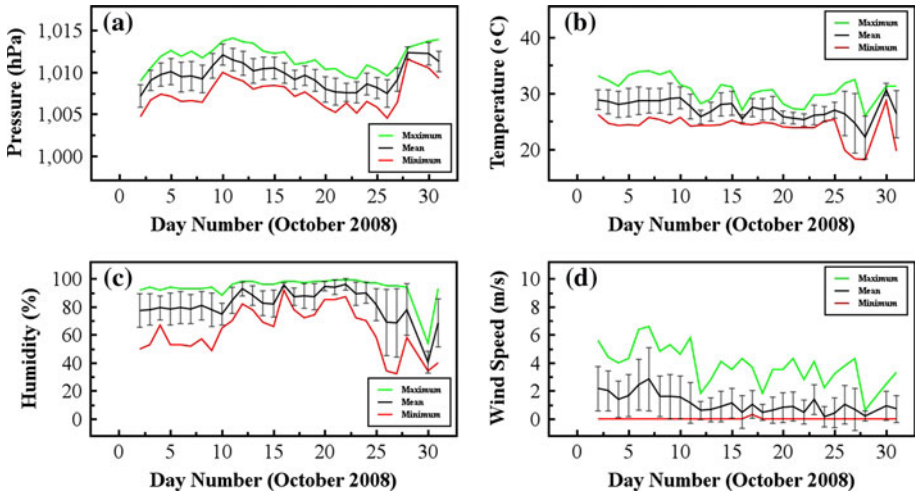

Fig. 2 Surface layer meteorological observations obtained from an Automatic Weather Station installed at SHAR for the month of October 2008: **a** surface layer pressure (hPa); **b** air temperature (°C); **c** relative humidity (%) and **d** wind speed (m/s). *Error bars* attached with the mean values indicate standard deviation of the parameter for that particular day

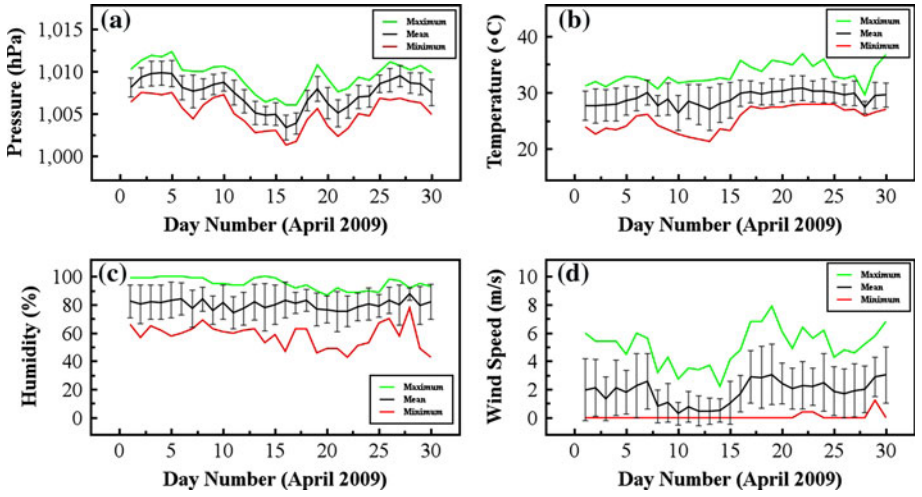

Fig. 3 Same as Fig. 2, but for the month of April 2009

experienced frequent rains from 11th of October to 24th of October 2008. Formally, the Indian Meteorological Department had declared 14th of October 2008 as the onset day of NE monsoon over the launch site (IMD Website: http://www.imd.gov.in/). During this period, total accumulated rainfall over SHAR went up to about 400 mm. On the other hand, SHAR did not experience any severe rainy events during C-12 campaign, as expected. But on April 13, an area of shower and thunderstorms became slightly organized over the central Bay of Bengal (BoB), and later an area of low pressure developed underneath the convection as the system developed (Fig. 5). Weak banding features also

Table 4 Statistics on monthly variation of surface layer meteorological observations at SHAR during October 2008 and April 2009, respectively

Sl. No.	Parameter		PSLV-C11 (October 2008)	PSLV-C12 (April 2009)
1.	Surface pressure (hPa)	Range	1004.40–1014.00	1001.30–1012.30
		Mean	1009.37	1007.27
		SD	0.08	2.23
2.	Air temperature (°C)	Range	18.16–33.99	21.29–36.88
		Mean	27.26	29.01
		SD	2.68	2.75
3.	Relative humidity (%)	Range	31.92–98.97	42.96–99.95
		Mean	82.47	80.09
		SD	13.73	11.78
4.	Wind speed (m/s)	Range	0.00–6.60	0.00–7.90
		Mean	1.60	2.04
		SD	1.40	1.85

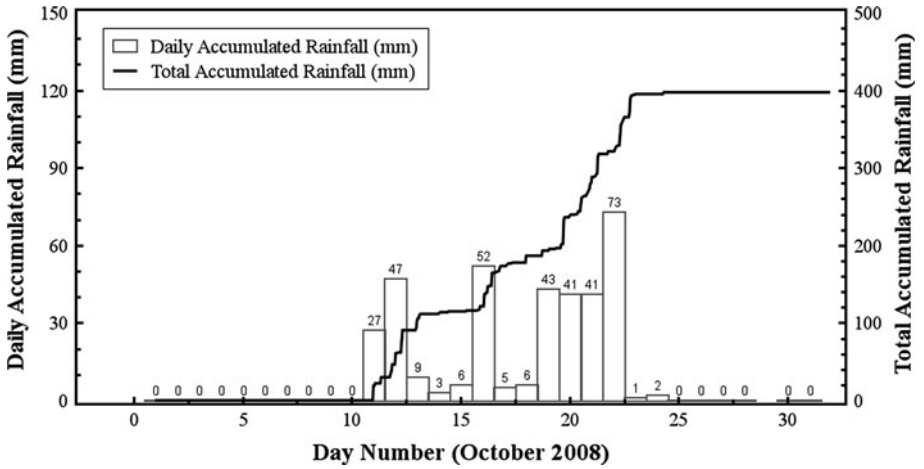

Fig. 4 Daily accumulated rainfall (*bars*) and total accumulated rainfall (*line*) for the month of October 2008

formed around the periphery of the storm. By April 14, deep convection persisted around the centre of circulation, and it was designated as depression. With its further intensification, finally this convective system was named as BIJLI cyclonic storm, which ultimately travelled north–north-eastward and dissipated by the mid of 16th of April 2009 (Fig. 5a–f). Its movement over the BoB and its immediate impact on the launch site were of great concern during C-12 campaign. In Fig. 5a–f, we show the cloud images over the subcontinent during 14th of April 2009 to 16th of April 2009 observed from Kalpana Satellite for qualitative assessment of the convective system prevailing over the BoB.

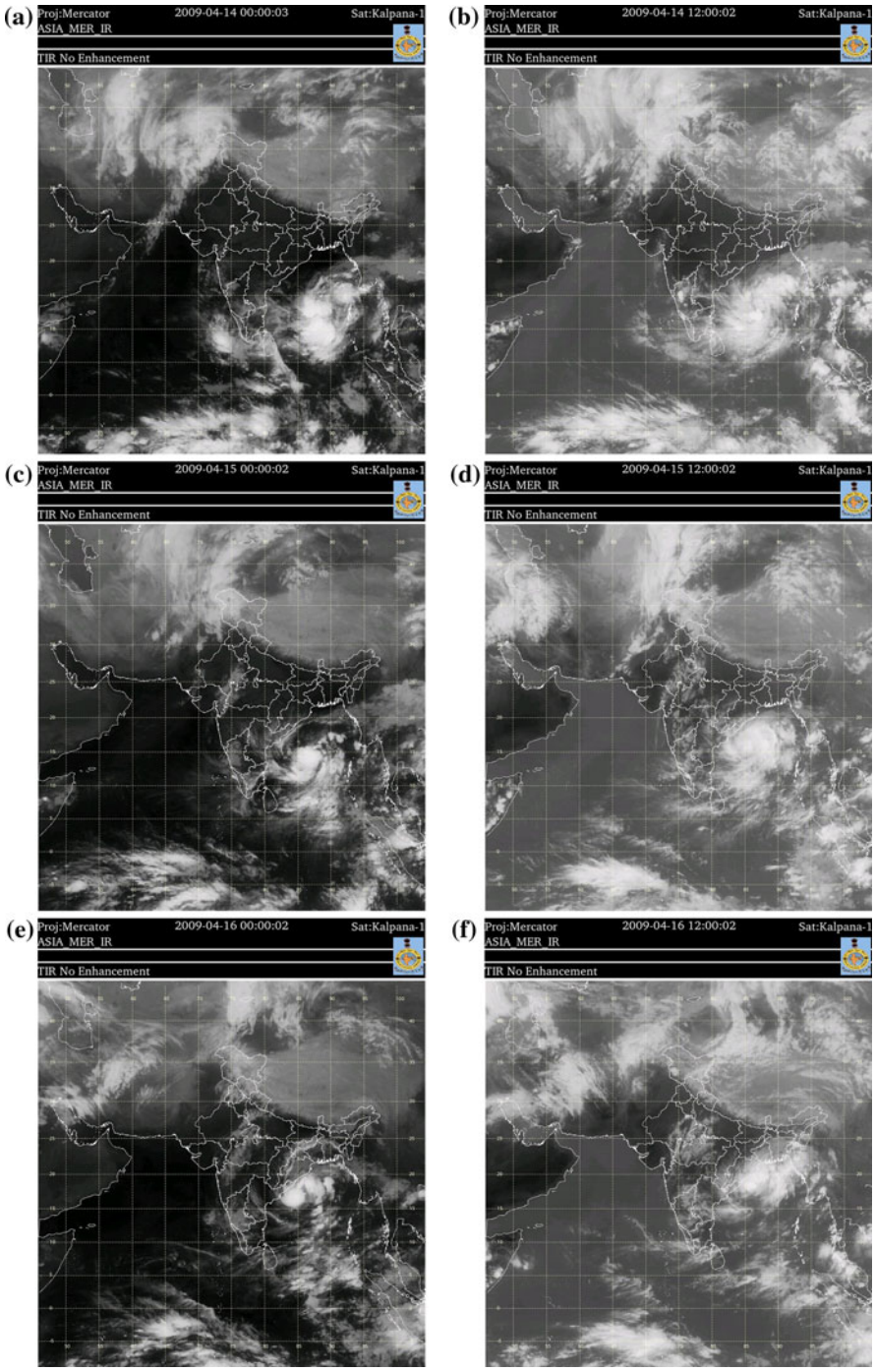

Fig. 5 KALPANA Satellite imagery of Clouds over the Indian subcontinent in IR channel during the passage of BIJLI cyclonic storm for **a** 14-April-2009: 00 GMT; **b** 14-April-2009: 12 GMT; **c** 15-April-2009: 00 GMT; **d** 15-April-2009: 12 GMT; **e** 16-April-2009: 00 GMT; **f** 16-April-2009: 12 GMT

4.2 Launch commit criteria (LCC)-related requirements

The launch weather guidelines involving the satellite launch activities for different launch vehicles and rockets are similar in many areas, but a distinction is maintained for the individual characteristics of each. These guidelines include weather trends and their possible effects on launch day. More importantly, these guidelines, often referred to as 'launch commit criteria (LCC)', are broadly conservative and assure avoidance of possible adverse conditions. They are reviewed for each individual launches. The LCC for a particular satellite launch activities essentially define the permissible limits of meteorological conditions prevailing over the site. During the countdown, formal weather briefing occurs at regular intervals with special emphasis on probability of adverse weather events on the launch site. For a perfect satellite launch, it is expected that there should neither be any precipitation or lightning (and electric fields with triggering potential) at the launch pad or within the flight path. If lightening is detected within 20 km of the launch pad or planned flight path within 30 min prior to launch window, it is not advisable to go ahead for the launch. As per the Kennedy Space Centre (KSC) Press Release (2000) on LCC, it is advised that the satellite launch should be kept on hold, if any part of the planned flight path is through a layer of thick convective clouds. However, launch can be shown green signal, if the cloud layer is a cirrus-like cloud which is never associated with convective clouds and shows no evidence of containing water droplets. A detailed description on LCC can be found online on NASA News Release from John F. Kennedy Space Centre (KSC Press 2000). Keeping the criticalities involved during the launch activities, it is highly desired to have greater accuracy on local weather. For this purpose, various atmospheric and oceanic measurements are taken on routine basis through different instruments such as Doppler weather radar, field mill, balloon-borne GPS sondes, portable automatic weather station and oceanic buoys to name a few. In addition to routine measurements, the project team related to satellite launch often required regularly updated weather prediction over the launch site, and it is in this regard that Space Physics Laboratory of Vikram Sarabhai Space Centre has adopted a unique approach by making use of two different atmospheric models—ARPS and HRM—for providing short-to-medium-range weather prediction. During C-11 campaign, the necessary information requirements were confined to the probability of thunderstorm occurrence during the launch window. On the contrary, the focus of numerical weather predictions through atmospheric models during C-12 campaign was confined to the formation and movement of BIJLI cyclonic storm and its impact on the launch site.

4.3 ARPS model simulations for prediction of thunderstorm occurrence

On 22nd of October 2008, ISRO successfully launched its maiden moon mission Chandrayaan-1 through PSLV-C11 carrier. As part of Chandrayaan-1 MET countdown activities, various atmospheric models ranging from global scale, regional scale to mesoscale were made operational at the launch site for providing regional weather forecast during the period of launch campaign. Since C-11 campaign was mostly influenced with frequent thundershowers and associated rainfall events, ARPS model was customized for SHAR domain and made operational for providing the probability of thunderstorm for +6 to +12 h, and forecast products were updated regularly in time during the launch window. The ARPS model was initialized with the vertical profiles of meteorological parameters obtained from the indigenously developed balloon-borne Pisharoty sondes (Satyanarayana 2008; Subrahamanyam et al. 2008). The entire exercise was focused on the consolidation

of the model-simulated parameters in a scientific and logical way to provide the probability of thunderstorm occurrence. For this purpose, five parameters obtained from ARPS simulations namely (1) hourly accumulated rainfall; (2) cloud and rain water mixing ratio; (3) vertical velocities; (4) low-level wind shear and (5) magnitude of surface layer specific humidity were chosen as the probable indicators of thunderstorm occurrence.

In Fig. 6, we show model-simulated time series of (a) hourly accumulated rainfall; (b) cloud water mixing ratio; (c) rain water mixing ratio and (d) vertical velocities between 21st of October 2008 (1915 LT) and 22nd of October 2008 (1915 LT). It may be noted that Chandrayaan-1 was launched through PSLV-C11 carrier in the morning hours around 0624 LT which was followed with an intense thunderstorm resulting into a moderate rain showers. With the model-simulated products, we attempt to examine how they were useful in providing logistic forecast on probability of thunderstorms/rainfall over the launch site. From Fig. 6a, it could be noticed that the model indicated favourable rainfall between 0615 and 1015 LT with a peak at about 0915 LT. Now, we examine time-series profiles of cloud and rain water mixing ratio in Fig. 6b, c; it is noticed that time slot of about four hours between 0615 and 1015 LT shows favourable conditions for occurrence of thunderstorms and moderate rainfall, where the lower atmosphere is sufficiently moist with high values cloud and rain water mixing ratio. Time-series profile of vertical velocities shown in Fig. 6d also indicates moderate downdraft activities during at about 0900 LT. While the model predicted heavy rainfall at about 0900 to 1000 LT, in reality SHAR experienced

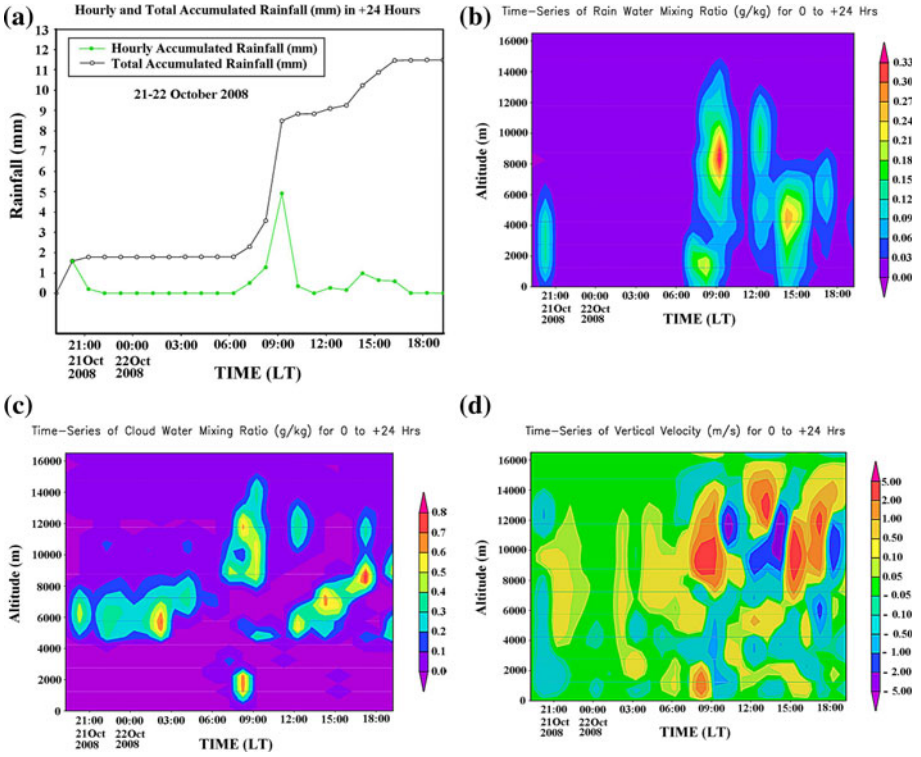

Fig. 6 ARPS Model simulations between 21st of October 2008 (1915 LT) and 22nd of October 2008 (1915 LT): **a** hourly accumulated rainfall (in mm); **b** time-series profile of cloud water mixing ratio (in g/kg); **c** time-series profile of rain water mixing ratio (g/kg); **d** time-series profile of vertical velocities (m/s)

heavy thundershowers immediately after the Chandrayaan-1 launch. These deviations and time lag can be attributed to some of the deficiency in model physics or the nature of highly localized rainfall, which probably were beyond the scope of model simulations. Nonetheless, during C-11 campaign, ARPS model simulations were found to be of great importance, as a careful examination of model-derived products such as hourly accumulated rainfall, cloud and rain water mixing ratio, vertical velocities and low-level wind shear could help in providing a logistic forecast on probability of thunderstorms. Through these products, we could capture more than 70% of rainfall slots successfully; however, there were a few localized events, where model did not capture the rainfall properly. Within the permissible constraints of the model, it was noticed that these parameters required hyper-tuning with greater accuracy and quantification.

4.4 HRM simulations during C-12 launch campaign

During C-12 launch campaign, the Bay of Bengal (BoB) underwent severe cyclonic storm named BIJLI between 14th and 16th April 2009 and it was one of the prime concerns with respect to LCC for PSLV-C12 launch-related activities. In this regard, HRM-simulated meteorological fields were found to be quite useful in inference of wind circulation prevailing over the launch site and adjoining BoB oceanic region. For qualitative assessment of HRM-simulated meteorological fields, we compare them with NCEP-FNL reanalysis for the concurrent period, which can be considered as the realistic observations. In Fig. 7, HRM-simulated wind vectors (+18 h forecast) for 1,000 hPa level valid for 14th of April 2009 (1800 GMT) are compared with the observations. A cyclonic circulation with low pressure over the head BoB at 1,000 and 850 hPa levels is clearly captured in simulations almost 18 h in advance (Figs. 7, 8). The steering wind circulation at 200 hPa for the concurrent timings also shows a very good comparison between the simulations and

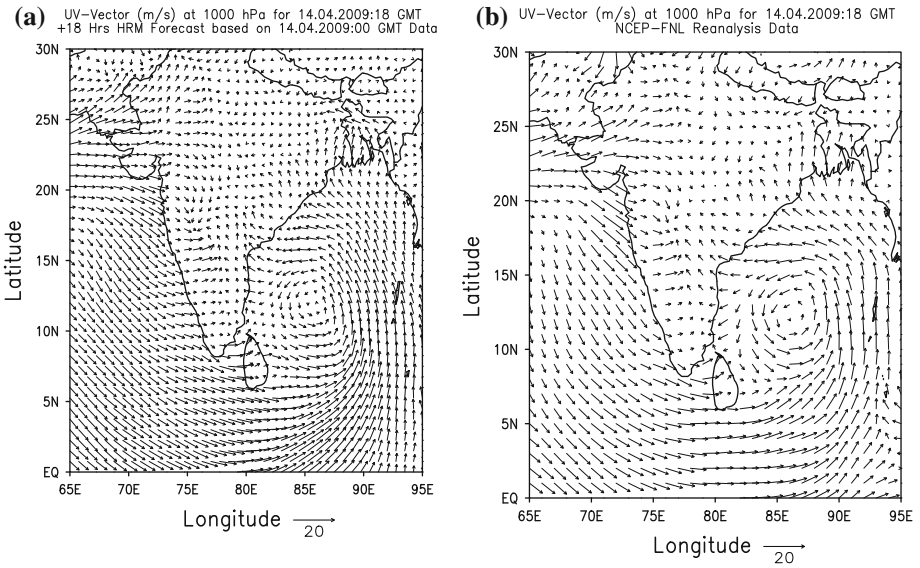

Fig. 7 Comparison of HRM-simulated wind vectors (+18 h forecast) for 1,000 hPa with NCEP-FNL reanalysis on 14th of April 2009 (1800 GMT)

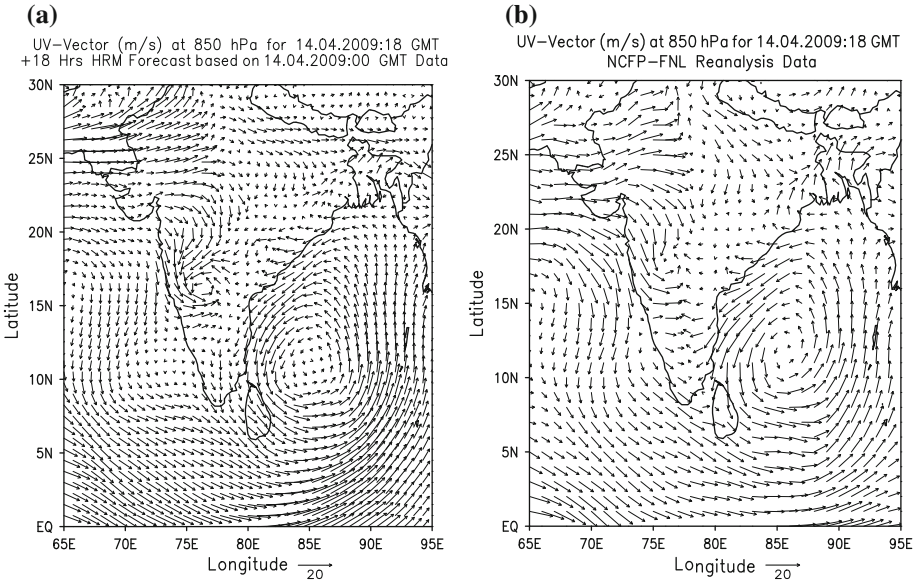

Fig. 8 Comparison of HRM-simulated wind vectors (+18 h forecast) for 850 hPa with NCEP-FNL reanalysis on 14th of April 2009 (1800 GMT)

reanalysis (Fig. 9). From Figs. 7–9, it is very interesting to note that—almost 18 h in advance—HRM simulations clearly indicated formation of a cyclonic storm over the head Bay of Bengal, and the wind circulation was regularly updated to the MET team at SHAR during the campaign, so as to assess its impact on the launch site. Since the cyclonic storm was formed quite away from the launch site, there was no severe impact on SHAR, and later in due passage of time, this cyclonic storm BIJLI moved further north–north-eastward before its landfall. During the passage of cyclonic storm, the amount of moisture at about 3 km (roughly 700 hPa) is often treated as one of the crucial parameters by the meteorologists to categorize the cyclone in terms of its intensity. Therefore, we show HRM simulation of relative humidity at 700 hPa on 16th of April 2009 (1800 GMT), when BIJLI cyclonic storm had advanced towards north-east part of the Indian subcontinent in Fig. 10a. Simulated field is also compared with the NCEP-FNL reanalysis, and results are quite encouraging, as almost all the gross features in relative humidity field with realistic magnitudes are nicely captured in +18-h simulations, thereby providing a strong justification of usage of HRM-simulated meteorological fields for LCC during launch activities.

5 Summary and concluding remarks

In the present research article, we describe the potential of two atmospheric models, namely ARPS and HRM, in providing valuable information with respect to LCC for satellite launch activities. The major outcome of the study can be summarized as:

1. A combination of two mesoscale atmospheric models HRM and ARPS are found to be of great importance in providing short-to-medium-range weather prediction over SHAR with a special emphasis on LCC-related meteorological information.

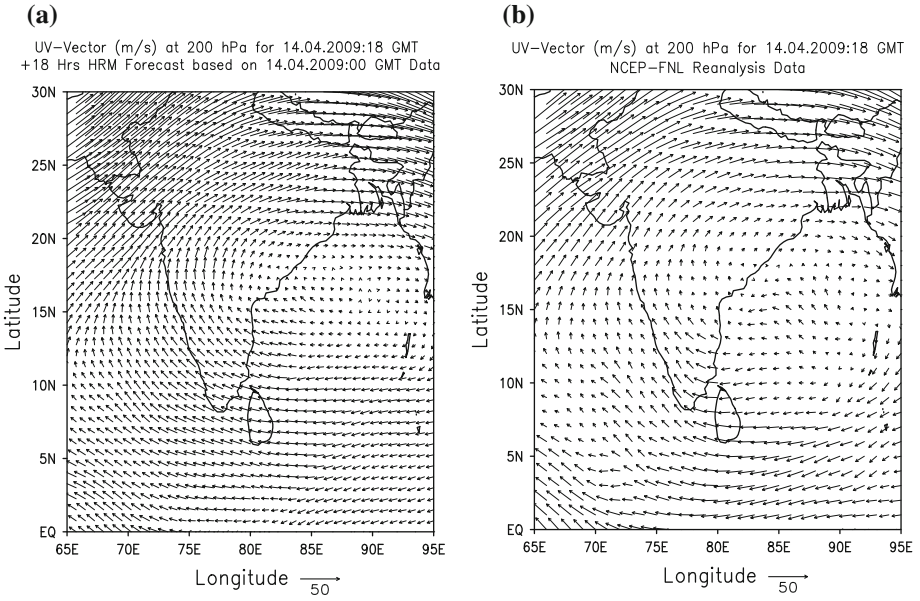

Fig. 9 Comparison of HRM-simulated wind vectors (+18 h forecast) for 200 hPa with NCEP-FNL reanalysis on 14th of April 2009 (1800 GMT)

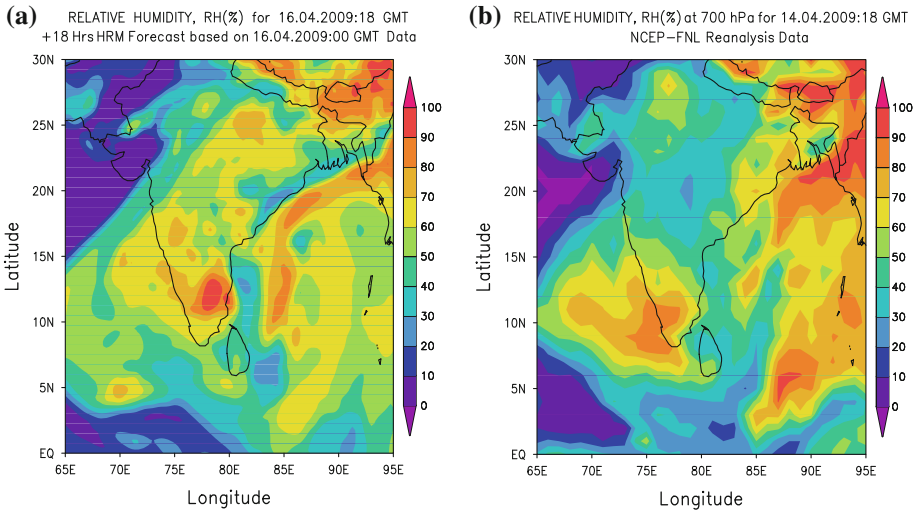

Fig. 10 Comparison of HRM-simulated relative humidity (+18 h forecast) for 700 hPa with NCEP-FNL reanalysis on 16th of April 2009 (1800 GMT)

2. Model-simulated meteorological fields during C-11 and C-12 launch campaigns when contrasting weather prevailed over SHAR, HRM and ARPS model could simulate synoptic and local weather conditions reasonably well.
3. During C-11 campaign, when SHAR experienced frequent thundershowers, a combination of four different products from ARPS model, namely accumulated

rainfall, cloud and rain water mixing ratio, low-level wind shear and vertical velocities were used in providing logistic forecast on probability of thunderstorms and rainfall time slots.

4. During C-12 campaign, when Bay of Bengal oceanic region experienced BIJLI cyclonic storm, HRM could simulate the formation of storm almost 18 h well in advance, and model-simulated meteorological fields during the episode were found to be well in tune with NCEP-FNL reanalysis for the concurrent timings.
5. In a broad perspective, HRM provides valuable information on severe weather event threat in a typical short-range timescale, which can be further studied in detail with the aid of highly localized ARPS model simulations.

In future, the present study would be extended to different seasons to assess the accuracies in model simulations and research direction would be focused on improvements in forecast fields through probable data assimilation in both the models.

Acknowledgments We greatly acknowledge the support and inspiring guidance rendered by Dr. K. Krishna Moorthy, Director, SPL and Prof. R. Sridharan, Former Director, SPL. Special words of thanks go to Mr. Thomas C. Babu of AERO Parallel Computing Facility, VSSC for his help in maintenance of LINUX Cluster System at SPL, where the HRM and ARPS model simulations were carried out. We wish to thank Dr. Detlev Majewski, Deutscher Wetterdienst, Germany and his colleagues for providing continuous support to us in smooth functioning of HRM. The NCEP-FNL reanalysis data for this study are from the Research Data Archive (RDA) which is maintained by the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). NCAR is sponsored by the National Science Foundation (NSF). The original data are available from the RDA (http://dss.ucar.edu) in data set number ds083.2. KALPANA Satellite images over the Indian subcontinent are downloaded from the Indian Meteorological Department (http://www.imd.gov.in/) and we duly acknowledge their services. Automatic Weather Station data for SHAR are made available to us through ISRO's PRWONAM Project (http://www.mosdac.gov.in/), and we acknowledge all the members of the project for their cooperation. One of the authors TJA would like to thank ISRO Research Fellowship for her PhD work.

References

Anthes RA, Warner TT (1974) Development of hydrodynamical models suitable for air pollution and other mesometeorological studies. Mon Weather Rev 106:1045–1078

Bannoon PR (1995) Hydrostatic adjustment: Lamb's problem. J Atmos Sci 52:1743–1752

Businger JA, Wyngaard JC, Izumi Y, Bradley EF (1971) Flux-profile relationships in the atmospheric surface layer. J Atmos Sci 28:181–189

Case JL, Manobianco J, Oram TD, Garner T, Blottman PF, Spratt SM (2002) Local data integration over East-Central Florida using the ARPS data analysis system. Weather Forecast 17:3–26

Cox R, Bauer BL, Smith T (1998) A mesoscale model intercomparison. Bull Am Meteorol Soc 79:265–283

Das S, Mithra AK, Iyengar GR, Singh J (2002) Skill of medium-range forecasts over the Indian region using different parameterizations of deep cumulus convection. Weather Forecast 17:1194–1210

Dudhia J (1993) A non-hydrostatic version of Penn State–NCAR mesoscale model: validation tests and simulation of an Atlantic cyclone and cold front. Mon Weather Rev 121:1493–1513

Heise E, Schrodin R (2002) A multi-layer soil model including freezing/melting processes. Res Activities Atmospheric Ocean Model 32:4.11–4.12 (WMO/TD-No. 1105)

Kain JS, Fritsch JM (1993) Convective parameterization for mesoscale models: the Kain-Fritsch scheme. The representation of cumulus convection in numerical models. Meteor Monogr 24(46), Amer Meteor Soc 165–170

KSC Press Release (2000) Space shuttle weather launch commit criteria and KSC end of mission weather landing criteria. Available via http://www-pao.ksc.nasa.gov/kscpao/release/2000/15-00.htm, Accessed: October 20, 2009

Kuo HL (1965) On formation and intensification of tropical cyclones through latent heat release by cumulus convection. J Atmos Sci 22:40–63

Kuo HL (1974) Further studies of the parameterization of the influence of cumulus convection on large scale flow. J Atmos Sci 31:1232–1240

Louis JF (1979) A parametric model of vertical eddy fluxes in the atmosphere. Bound-Layer Meteor 17:187–202

Majewski D (2009) HRM-user's guide. Deutsche Wetter Dienst (DWD). Offenbach, Germany, p 124

Manikiam B, Nayak MM, Jeyamani M, Shoba TS (2008) Satellite linked automatic weather station (AWS). In: Mainikiam B, Murthy TGK (eds) Technology development for atmospheric research and applications. Atmospheric Science Programme Office, Indian Space Research Organization, Bangalore, pp 9–37

Manobianco J, Zack W, Taylor GE (1996) Work station based real-time mesoscale modeling designed for weather support to operations at the Kennedy Space Center and Cape Canaveral Air Station. Bull Am Meteorol Soc 77:653–672

Mellor GL, Yamada T (1974) A hierarchy of turbulence closure models for planetary boundary layers. J Atmos Sci 31:1791–1806

Noilhan J, Planton S (1989) A simple parameterization of land surface processes for meteorological models. Mon Wea Rev 117:536–549

Pielke RA (1984) Mesoscale meteorological modeling. Academic Press, Orlando, p 612

Pleim JE, Xiu A (1995) Development and testing of a surface flux and planetary boundary layer model for application in mesoscale models. J Appl Meteorol 34:16–32

Radhika R (2008) DWR data assimilation in numerical weather prediction for forecast of thunderstorms at Sriharikota. In: Mainikiam B, Murthy TGK (eds) Technology development for atmospheric research and applications. Atmospheric Science Programme Office, Indian Space Research Organization, Bangalore, pp 463–487

Radhika R, Mohanty UC, Pattanayak S, Mandal M, Indira Rani S (2006) Location specific forecast at Sriharikota during the launch of GSLV-01. Curr Sci 91(3):285–295

Rakesh V, Singh R, Pal PK, Joshi PC (2007) Sensitivity of mesoscale model forecast during a satellite launch to different cumulus parameterization schemes in MM5. Pure Appl Geophys 164:1617–1637

Ritter B, Geleyn JF (1992) A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. Mon Weather Rev 120:303–325

Satyanarayana S (2008) GPS radiosonde development, technology development for atmospheric research and applications. In: Mainikiam B, Murthy TGK (eds) Technology development for atmospheric research and applications. Atmospheric Science Programme Office, Indian Space Research Organization, Bangalore, pp 142–188

Singh R, Pal PK, Kishtawal CM, Joshi PC (2005) Impact of bogus vortex for track and intensity prediction of tropical cyclone. J Earth Syst Sci 114:427–436

Snook JS, Stamus PA, Edwards J, Christidis Z, Mcginley JA (1977) Local domain mesocale analysis and forecasting model output for the 1996 summer Olympic games. Weather Forecast 13:138–150

Subrahamanyam DB, Radhika R, Kunhikrishnan PK (2006) Improvements in simulations of atmospheric boundary layer parameters through data assimilation in ARPS mesoscale atmospheric model. In: Krishnamurti TN, Goswami BN, Iwasaki T (eds) Remote sensing of atmospheres and oceans, proceedings of SPIE, vol 6404, pp 1–10. doi:10.1117/12.694106

Subrahamanyam DB, Indira Rani S, Ramachandran R, Kunhikrishnan PK (2008) Nudging of vertical profiles of meteorological parameters in one-dimensional atmospheric model: a step towards improvements in numerical simulations. Ocean Sci J 43(4):165–173

Tiedtke M (1989) A comprehensive mass flux scheme for cumulus parameterization in large scale models. Mon Weather Rev 117:1779–1800

Xue M, Droegemeier KK, Wong V, Shapiro A, Brewster K (1995) ARPS Version 4.0 users's guide, CAPS NSF, FAA, University of Oklahama, USA, pp 380

Xue M, Droegemeier KK, Wong V (2000) The advanced regional prediction system (ARPS)—a multi-scale nonhydrostatic atmospheric simulation and prediction model. Part I: model dynamics and verification. Meteorol Atmos Phys 75:161–193

Xue M, Droegemeier KK, Wong V, Shapiro A, Brewster K, Carrl F, Weber D, Liu Y, Wang D (2001) The advanced regional prediction system (ARPS)—a multi-scale nonhydrostatic atmospheric simulation and prediction tool. Part II: model physics and applications. Meteorol Atmos Phys 76:143–165

Xue M, Wang D, Gao J, Brewster K, Droegemeier KK (2003) The advanced regional prediction system (ARPS), storm-scale numerical weather prediction and data assimilation. Meteorol Atmos Phys 82:139–170. doi:10.1007/s00703-001-0595-6